Available online at www.sciencedirect.com
ScienceDirect
Procedia Structural Integrity 2 (2016) 430–437
Structural Integrity Procedia
www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

General effects of pulse electric breakdown of dielectric gaps and dynamic failure of continuous media

Yuri Petrov and Ivan Smirnov*

Saint Petersburg University, Universitetskaya nab. 7/9, St. Petersburg, 199034, Russia

Abstract

In this paper we consider some general effects observed at pulse electric breakdown of dielectric gaps and dynamic failure of continuous media. The effect of time and strain rate dependence of limiting characteristics, the substitution effect of maximal strength, as well as failure and breakdown with delay are considered. Despite the different physical nature of mechanical failure and electrical breakdown, these effects can be modeled based on a common approach of the incubation time criterion. It is discussed that the strain/stress rate dependence of strength and the volt-time characteristic of a dielectric medium cannot be used as a universal characteristic of the material's mechanical and dielectric strength and should be determined for each specific case. It is shown that the time parameter, which is invariant to the action history, is more appropriate as a characteristic of the dynamic strength. With the incubation time criterion one can construct a unified time dependence of the mechanical or electrical strength consisting of quasi-static and dynamic regimes of action.

Keywords: dynamic failure; pulse electric breakdown; the incubation time criterion; strain rate dependence; volt-time characteristic; strength substitution effect; failure delay.

1. Introduction

Research results on dynamic failure of continuous media and pulsed electrical breakdown of dielectric gaps exhibit a number of effects, which are common to these seemingly quite different physical processes. The effects relate to a fundamental difference between the behavior of medium under dynamic and quasi-static actions. For

* Corresponding author.
E-mail address: i.v.smirnov@spbu.ru

10.1016/j.prostr.2016.06.056

example, one of the main problems of determining the dynamic strength properties is associated with the functional dependence of limiting characteristics on the history and method of applying a load. Whereas a limiting characteristic is a constant for a material in the static case, limiting characteristics in dynamics are strongly unstable and, as a result, their behavior becomes unpredictable. In the case of the mechanical rupture or compression, the dynamic strength is usually expressed by the experimentally measured strain rate dependence of limiting stresses, see e.g. Antoun et al. (2003) and Freund (1990). In the case of the electric breakdown, the dynamic electric strength is usually expressed by the experimentally measured voltage–time characteristic, see e.g. Vavilov and Mesyats (1970) and Mesyats et al. (1972).

Other typical effects of the behavior of medium under dynamic actions are the change of maximum strength of two materials (Petrov et al. 2013, Vorob'ev 1998) and a delay of failure (breakdown) (Antoun et al. 2003, Kuznetsov et al. 2011). The change of maximum strength of two materials or the substitution effect is that one material can have a greater quasi-static strength than the other material, but the second material can withstand more high dynamic loads than the first. The delay of failure (breakdown) corresponds to failure (breakdown) at the time of a reduction of stress in the material (electric field between gaps).

In this paper, we analyze examples illustrating typical dynamic effects inherent in the processes of mechanical failure and electrical breakdown. We propose a unified interpretation for the failure of continuous media and electrical breakdown of dielectric gaps using the structural-time approach (Petrov and Morozov 1994) based on the concept of the failure incubation time criterion (Petrov 2004).

2. Calculation of limiting characteristics

Under slow action, there is a phenomenological approach for evaluation of the limiting fields, which proves to be a reasonably efficient tool of modeling and prediction of the electric and mechanical strength:

$$F(t) \geq F_c \tag{1},$$

where $F(t)$ is the intensity of a local force field causing the failure of the medium; F_c is the limit intensity of the local force filed, which can depend on many material and geometrical factors; t is the time.

The basic cause of difficulties in modeling the dynamic effects of mechanical or electrical strength is the absence of an adequate limiting condition that determines the instant of rupture or breakdown. This problem can be solved by using both the structural macro mechanics of failure and the concept of the failure incubation time, which represents the kinetic processes of macroscopic breaks formation (Morozov and Petrov 2000). The dynamic effects become essential for actions whose periods are comparable with the scale determined by the failure incubation time associated with preparatory processes of developing micro defects in the material structure.

The criterion of the failure incubation time makes it possible to calculate effects of the unstable behavior of dynamic-strength characteristics. This criterion can be generalized in the form of the condition (Petrov 2004)

$$\frac{1}{\tau}\int_{t^*-\tau}^{t^*} \frac{F(t)}{F_c}dt \geq 1 \tag{2},$$

where $F(t)$ is the intensity of a local force field causing the failure of the medium; F_c is the static critical intensity of the local force filed; τ is the incubation time associated with the dynamics of a process preparing the break. The time of failure or breakdown t^* is defined as the time at which the condition (2) becomes an equality.

Depending on the physics of the process, the local force field can correspond to the stress in the place of failure or the electric field between the electrodes. The static critical intensity of the field is determined by standard experiments. If the local force field and the time of the break can be registered in an experiment, then the condition (2) has only one unknown - the incubation time. This parameter can be defined by fitting the condition (2) to the experimental points.

According to the terminology of the approach of the failure incubation time, the static critical intensity of the local force filed characterizes the material strength under slow actions, and the incubation time characterizes the material strength under dynamic actions. Thus, knowing only two parameters (F_c, τ), one can find different dependencies and parameters, such as current–voltage characteristics, limiting stress at different strain rates, breakdown time, etc.

3. Effects of dynamic actions

3.1. Time dependence of limiting characteristics

A typical example illustrating the complicated behavior of the dynamic mechanical strength of medium is the time dependence of strength observed at spall fracture of solids (Zlatin et al. 1974) and cavitation of liquids (Besov et al. 2001), see Fig. 1. This dependence of the fracture time t^* on the critical pulse amplitude F^* for different pulse durations shows that the dynamic strength is not a material constant but depends on the time to fracture (i.e., sample "life time"). The criterion of critical action (1) describes well long-term quasi-static failure/breakdown caused by long-duration wave pulses. However, in the case of short-duration pulses, the fracture time weakly depends on the threshold pulse amplitude, and this dependence has a certain asymptote. This effect is called the phenomenon of the dynamical branch of the strength time dependence. Neither the conventional theory of strength nor the known time criteria explains this phenomenon. The total time dependence of strength can be obtained on the basis of the incubation time criterion (2).

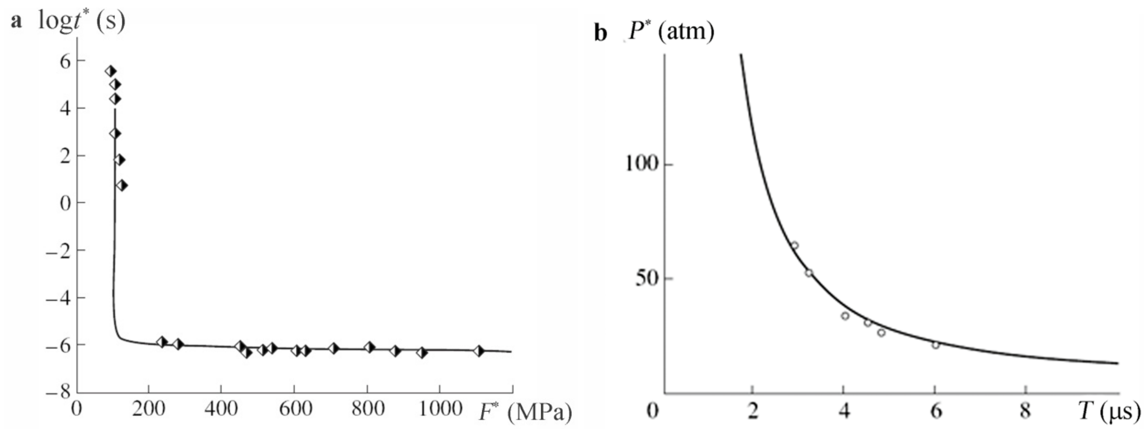

Fig. 1. Time dependence of limiting characteristics calculated by Petrov (2004). (a) Logarithm of the fracture-process duration t^* vs. the threshold amplitude F^* of a stress pulse that causes spall fracture in aluminum samples (Zlatin et al. 1974); (b) Mechanical strength of water P^* as a function of the pulse duration T (Besov et al. 2001).

The schemes for the application of the criterion (2) to spall problems are given by Petrov et al. (2010). An example of a calculation using the criterion (2) for the time dependence of the spall strength of aluminium for triangular pulses realized in the experiments reported by Zlatin et al. (1974) is represented in Fig. 1 by the solid curve. The calculated parameters of the material are $\tau = 0.45$ μs and $F_c = 103$ MPa.

The experiments of Besov et al. (2001) show that the cavitation strength of liquids increases nonlinearly with decrease of loading-pulse duration. Using the incubation time criterion (2) makes it possible to calculate the experimentally observed increase in the cavitation threshold $P*$ with decreasing the pulse duration T (Fig.1b). The calculation was made for the static critical pressure $P_c = 1$ atm and the incubation time $\tau = 19$ μs.

The above effect is also observed in pulsed electrical breakdown of dielectric gaps. The typical feature of pulsed breakdown is an increase in the breakdown voltage with reducing pulse duration. As an example, the breakdown electric field E^* measured by Khaneft (2000) for ammonium perchlorate single crystals is presented in Fig. 2 as a function of the duration T of the leading edge of the pulse. This dependence also characterizes the electrical strength as a function of the voltage growth rate in a sample and can be called the time dependence of strength by analogy with the above examples of spall fracture and cavitation.

The curves in Fig. 2 are the time dependences for the electrical strength of ammonium perchlorate calculated by Petrov (2004) according to the criterion (2) with the incubation time $\tau = 0.33$ μs, the static electrical strength $E_c = 0.52\times10^6$ V/cm and $E_c = 0.2\times10^6$ V/cm for different material thicknesses h = 0.01 and 0.03 cm, respectively. The onset time of increasing the breakdown field in the dependences plotted in Fig. 2 is entirely determined by the τ value. As was shown by Khaneft (2000), this time was virtually independent of the interelectrode distance. This indicates that the incubation time in the case under discussion may be considered as a material characteristic.

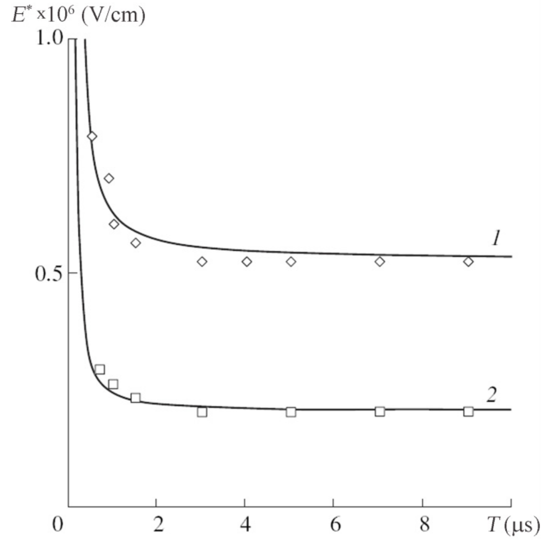

Fig. 2. Electrical strength E^* of ammonium perchlorate vs. the duration T of the leading edge of an electrical pulse for the interelectrode gaps h = 0.1 cm - (1) and 0.03 cm – (2) received by Khaneft (2000) and calculated by Petrov (2004).

Note that Fig. 1 and 2 reveal two branches of the time dependence belonging to the slow quasi-static and fast dynamic input of energy. The quasi-static branch depends mainly on the parameter F_c, whereas the dynamic branch is caused by approaching the values of characteristic times of applied loads to the duration of the failure incubation period τ. Thus, τ can be considered as the parameter integrally describing the dynamic strength of a material.

3.2. Substitution effect of maximal strength

A construction material is selected on the basis of its ability to withstand a certain stress (as one of the defining parameters). There is a set of test standards governing determination of the ultimate strength of a material under quasi-static tension, compression, bending, etc. However, tests under dynamic loading conditions show essential differences of dynamic strength characteristics in comparison with those of quasi-static tests. Under dynamic loading the critical stresses are characterized by very strong instabilities and cannot consider as material parameters. Moreover, the dynamic loads may lead to an unexpected substitution effect of maximal strength. A material, which has a lower strength compared to another material in quasi-static tests, can have greater strength under dynamic loading.

Fig. 3 shows the results of split tests of the fibre reinforced concrete (CARDIFRC) and gabbro-diabase under quasi-static and high strain rates on a semi-logarithmic scale. The tests were carried out using the modification of Kolsky method for dynamic splitting (the Brazil test). Detailed schemes of tests and results are presented in work of Bragov et al. (2003) for gabbro-diabase and in work of Bragov et al. (2012) for CARDIFRC. The curves in Fig. 3

correspond to the calculation by the criterion (2) with the following parameter values: F_c = 23 MPa and τ = 15 µs for concrete and F_c = 18 MPa and τ = 70 µs for gabbro-diabase. It is clear from the results that carrying capacity of both materials increases with the growth of loading rate. However, although CARDIFRC has a higher quasi-static split strength than that of gabbro-diabase, its dynamic carrying capacity in splitting is lower at high stress rates (>$10^{2.5}$).

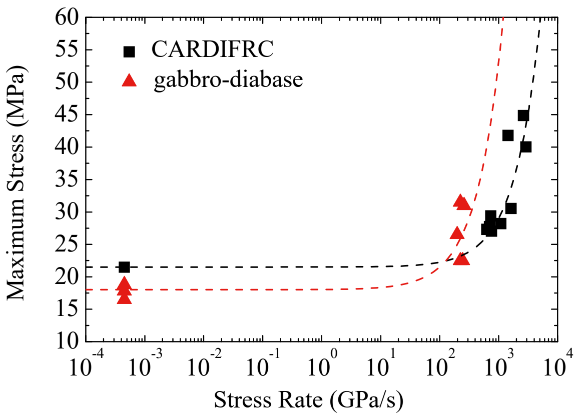

Fig. 3. The split tests of CARDIFRC and gabbro-diabase. Black squares are the experimental values for CARDIFRC (Bragov et al. 2012); black line is predictions of Eq. (2) for CARDIFRC (Petrov et al. 2013); red triangles are the experimental values for gabro-diabase (Bragov et al. 2003); and red dashed is predictions of Eq. (2) for gabro-diabase (Petrov et al. 2013).

The similar effect can be observed at the development of the breakdown channel in liquid or solid dielectrics in dependence on the steepness of the voltage pulse front. For example, if the electric strength of solid dielectrics often exceeds the strength of liquid dielectric media at a slow quasi-static input of energy, the electric strength of liquids can occur higher than the strength of solid dielectric materials including rocks at a fast pulse voltage (Vorob'ev et al. 1998).

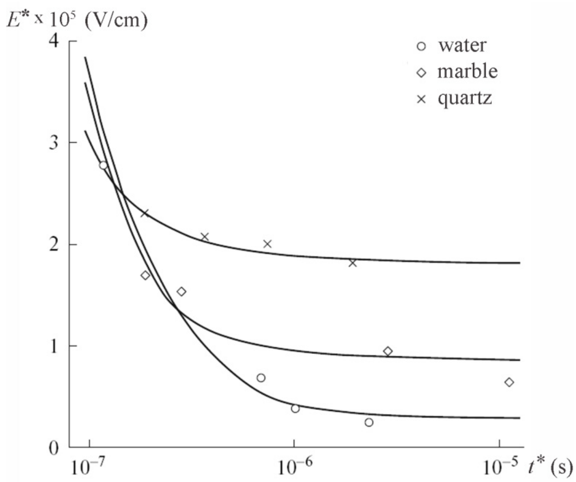

Fig. 4. Dependencies of electric strength on the time of breakdown for various media calculated on the basis of criterion (2) (Petrov 2014) and experimental ones (Vorob'ev et al. 1971).

Using the criterion (2) for analysis of particular experiments of Vorob'ev et al. (1971) for the interelectrode gap filled with liquid or solid dielectric, it is possible to obtain the voltage-time characteristics corresponding to various parameters of breakdown media. Fig. 4 shows the experimental and the calculated time dependencies of the electric strength for various media. The curves were calculated by Petrov (2014) with the following parameters: $\tau = 0.65\times10^{-6}$ s and $E_c = 2.8\times10^4$ V/cm for water; $\tau = 0.2\times10^{-6}$ s and $E_c = 8.5\times10^4$ V/cm for marble; $\tau = 0.08\times10^{-6}$ s and $E_c = 1.8\times10^5$ V/cm for quartz.

It can be seen that with increasing the steepness of the voltage pulse front and correspondingly decreasing the breakdown time t^*, the ratio between the breakdown voltages for different media can be changed to the opposite. In particular, water having substantially lower static strength can be broken down at appreciably higher electric field intensities than rock in the case of fast input of energy. In this case, it is possible to assert that the dynamic strengths of the compared media are arranged in inverse order as compared with their quasi-static strengths E_c expressed in terms of the incubation time τ.

3.3. Failure and breakdown with delay

Since the critical stresses at dynamic loads are unstable, it is usual to plot diagrams of strain/stress rate dependence of the strength. In this case, each loading or strain rate corresponds to one's critical stress. These diagrams are taken as a material property.

So dynamic strength is related to the strain rate without regard for the load time and shape. However, as the analysis shows (see e.g. Petrov and Utkiv 2015), the action time and the applied pulse shape and amplitude equally determine the critical fracture characteristics.

The shape and parameters of action on medium are often determined by the characteristics of the facility used for tests (e.g., the flyer plate thickness, the capacity and the inductance of an electric charging unit, the laser power). At the same time, one of the specific features of failure or breakdown during dynamic loading is the possibility of application of an action that is highly than the critical action, which is required to break the material.

Let the action shape (it can be an isosceles or right-angled triangle) and action time T be specified. Let a pulse action of a given shape that results in failure (or breakdown) be the minimum breaking pulse if its decrease is due to a decrease in the amplitude or the time does not cause failure (or breakdown). If the applied pulse is higher than the minimum required pulse, we can speak about failure (or breakdown) with overloading.

If the failure (or electrical breakdown) occurs after the passage of the peak of the local stress (or an electric field), then we say that the failure (or electrical breakdown) is delayed. The time elapsed from the peak of the pulse until the moment of break characterizes the delay. Thus, the delay duration depends on the shape and overload of an action pulse. Therefore, the time of the break and the critical value of the local force field are determined by the pulse shape and the magnitude of the overload.

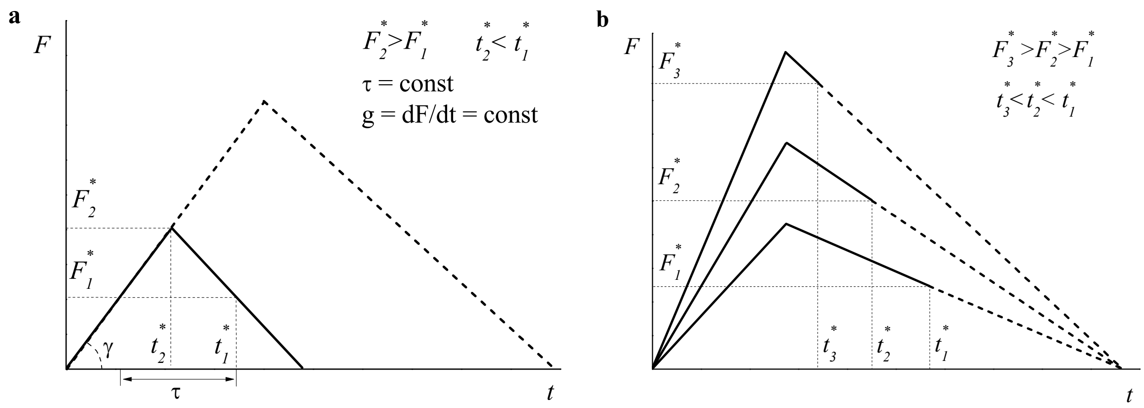

Fig. 5. Some possible variants of failure or electrical breakdown with a delay. F^*_i is the critical local force field; t^*_i is the time of break. (a) pulses with the same action rate; (b) pulses with the different action rate.

Fig. 5 shows some variants of failure or electrical breakdown with the delay. Pulses with the same action rate can lead to the break both the leading edge of the pulse and the trailing edge of the pulse, Fig.5a. Increasing an action rate at a constant duration of the action leads to the pulse overload and reduction of the delay, Fig.5b.

Experimental studies of the delay were carried out, for example, by Zlatin et al. (1974) for spall fracture and Kuznetsov et al. (2011) for electrical breakdown. Since failure and breakdown can occur at the trailing edge of the action pulse, it becomes clear that break depends primarily on the evolution of the process over a certain preceding time interval rather than on the instantaneous value of the effective force field. Integral basis of criteria (2) allows describing this effect.

The studies of temporal effects of failure and electric breakdown in terms of the incubation time criterion were carried out by Petrov et al. (2010) and Petrov et al. (2015). It was shown that the diagrams of the strain rate dependence of medium strength (see e.g. Fig. 3) and the volt-time characteristics (see e.g. Fig. 2) of medium cannot be considered as properties of this medium. A result of any dynamic actions should be assessed separately on the basis of simple and clear engineering principles.

4. Conclusion

The effect of time and strain rate dependence of limiting characteristics, the substitution effect of maximal strength, as well as failure and breakdown with delay characterize the nature of medium behavior under dynamic actions. These effects show the fundamental importance of investigating incubation processes preparing abrupt structural changes (failure and phase transitions) in continua medium under intense pulsed actions. The parameter with dimensions of time can be a universal basic characteristic of the dynamic strength and should become one of the main material parameters to be experimentally determined.

The considered results show that the structural-time approach based on the incubation time criterion is fundamental and makes it possible to adequately represent the dynamics of both the failure of continuous media and electrical breakdown of dielectric gaps. The presence of such effective criteria predicting the mechanical and electrical strength of a medium in simple engineering terms is vital for application in practice, and it can help eliminate the need to conduct laborious research of material behavior in a wide range of action conditions.

Acknowledgements

This work was supported by St. Petersburg State University (grant no. 6.38.243.2014).

References

Antoun, T., Seaman, L., Curran, D.R., Kanel, G.I., Razorenov, S.V., Utkin, A.V., 2003. Spall Fracture. Springer, 417 p.

Besov, A.S., Kedrinskii, V.K., Morozov, N.F., Petrov, Yu.V., Utkin, A.A., 2001. On the Similarity of the Initial Stage of Failure of Solids and Liquids under Impulse Loading. Doklady Physics 46(5), 363-365.

Bragov, A.M., Bolshakov, A.P., Gerdyukov, N.N., Lomunov, A.K., Novikov, S.A., Sergeichev, I.V., 2003. Research of Dynamic Properties of Some Rocks. In: International Conference "V Kharitonov thematic scientific reading", VNIIEF, Sarov, p. 43.

Bragov, A.M., Karihaloo, B.L., Petrov, Yu.V., Konstantinov, A.Yu., Lamzin, D.A., Lomunov, A.K., Smirnov, I.V. 2012. High-Rate Deformation and Fracture of Fiber Reinforced Concrete. J. of Applied Mechanics and Technical Physics, 53(6), 926.

Freund, L.B., 1998. Dynamic Fracture Mechanics. Cambridge University Press, 584 p.

Khaneft, I.G., Khaneft, A.V., 2000. Effect of the Duration of the Front Edge of the Voltage Pulse on the Electric Breakdown of Ammonium Perchlorate. Technical Physics 45(4), 423-426.

Kuznetsov, Yu.I., Vazhov, V.F., Zhurkov, M.Yu., 2011, Electrical Breakdown of Solid Dielectrics and Rocks on the Trailing Edge of a Voltage Pulse. Russian Physics Journal 54, 410.

Mesyats, G.A., Bychkov, Yu.I., Kremnev, V.V., 1972. Pulsed Nanosecond Electric Discharges in Gases. Sov. Phys. Usp. 15, 282–297.

Morozov, N. and Petrov, Y., 2000. Dynamics of Fracture. Springer, 98 p.

Petrov, Y., Morozov, N., 1994. On the Modeling of Fracture of Brittle Solids. ASME J Appl Mech 61, 710-712.

Petrov, Y.V., 2004. Incubation Time Criterion and the Pulsed Strength of Continua: Fracture, Cavitation, and Electrical Breakdown. Doklady Physics 49(4), 246–249.

Petrov, Yu.V., Smirnov, I.V., and Utkin, A.A., 2010. Effects of Strain-Rate Strength Dependence in Nanosecond Load Duration Range. Mechanics of Solids 45(3), 476-484.

Petrov, Y., Smirnov, I., Evstifeev, A., Selyutina, N., 2013. Temporal Peculiarities of Brittle Fracture of Rocks and Concrete. Frattura ed Integrità Strutturale 24, 112-118.

Petrov, Y., 2014. Structural-Time Criterion of Pulsed Electric Strength. Doklady Physics 59(1), 56–58.

Petrov, Y.V., and Utkin. A.A., 2015. Time Dependence of the Spall Strength under Nanosecond Loading. Technical Physics 60(8), 1162–1166.

Petrov, Yu.V., Morozov, V.A., Smirnov, I.V., Lukin, A.A., 2015. Electrical Breakdown of a Dielectric on the Voltage Pulse Trailing Edge: Investigation in Terms of the Incubation Time Concept. Technical Physics 60(12), 1733-1737.

Vavilov, S.P., Mesyats, G. A., 1970. Current Growth During Pulsed Breakdown of Millimeter Gaps in Vacuum. Soviet Physics Journal 13(8), 1058-1061.

Vorob’ev, A.A., Vorob’ev, G. A., Zavadovskaya, E.K., et al., 1971. Pulse Breakdown and Fracture of Dielectrics and Rocks. Tomsk University, Tomsk, 228 p. (in Russian)

Vorob’ev, A.A., Vorob’ev, G. A., Chepikov, A.T., 1998. Regularity of Breakdown in Solid–Liquid Dielectric Interface under a Pulse of Voltage. Inventor’s Certificate No. A-122.

Zlatin, N.A., Mochalov, S.M., Pugachev, G.S., and Bragov, A.M., 1974. Temporal Features of Fracture in Metals under Pulsed Intense Actions. Sov. Phys. Solid State 16, 1137-1140.